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TECHNICAL NOTE

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PROPOSAL FOR DETERMINING THE MASS OF LIQUID PROPELLANT

WITHIN A SPACE VEHICLE PROPELLANT TANK SUBJECTED TO

A ZERO GRAVITY ENVIRONMENT

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SUMMARY

A liquid propellant mass measurement system is proposed for the
zero gravity environment. The known thermodynamic relationships for
the liquid propellant and helium gas concomitant with state of the art
instrumentation are used to provide a system comparable with present
day terrestrial mass measuring systems.

In particular, the operation of the system is outlined for the
propellant transfer method and for the determination of leaks and
leakage rates.

A second concept which is a simplified version of the proposed
mass measurement system is introduced and discussed.

SECTION I.   INTRODUCTION

In any manned space flight mission, it should be possible to
determine the quantity of individual propellants contained onboard at
any time. Thus, a requirement exists for an onboard propellant mass
measurement system which is operable in a zero-gravity environment. A
system is proposed and applied to the orbital tanking mode. This system
is generalized and made applicable to any stage propellant tank.

SECTION II.   PROPOSED MASS MEASUREMENT SYSTEM

The proposed concept for determining the mass of propellant within
an orbiting space vehicle assumes a nonvented system. The mass of pro-
pellant within a vehicle propellant tank can be determined by knowing

the total volume of physical properties of the liquid propellant contained therein. By monitoring the pressure and temperature of a known mass of helium gas within the propellant tank and the pressure and temperature of the propellant, the gas laws may be utilized to determine the propellant mass within the tank.

FIGURE 1 shows a schematic of a vehicle propellant tank of known water volume which is corrected for low temperature shrinkage. A small sphere (or cylinder) of high-pressure helium gas and a flexible thin wall bladder are installed. The bladder is provided to separate the helium and propellant. The propellant tank is also instrumented with temperature and pressure probes.

A. DETERMINATION OF PROPELLANT MASS TRANSFERRED

1. The vehicle propellant tank is purged of foreign gases and precooled with liquid propellant prior to launch. The tank contains propellant vapor and residual liquid propellant when it is launched and placed in orbit.

2. Rendezvous of the vehicle and an orbital tanker is made (FIGURE 2a) and propellant transfer is initiated.

3. At some time during the transfer process, the helium is released within the bladder (FIGURE 2b). Pressure within the bladder is then equal to or slightly greater than the tank pressure. If a pressure differential exists across the bladder, it will subsequently be reduced to zero with continued propellant transfer.

4. Propellant transfer continues until the tank pressure surpasses the vapor pressure of the propellant. The propellant is then in a subcooled state (FIGURE 2c).

5. Now only liquid propellant and helium gas are within the tank; consequently, the mass of liquid propellant can be determined. The volume of helium gas is established with the gas laws as follows:

$$V_H = \frac{M_H Z_H R_H T_H}{P_H}$$

where V_H = total volume of helium

M_H = mass of helium

R_H = gas constant for helium

T_H = temperature of helium

P_H = pressure of helium

Z_H = compressibility factor for helium

The volume occupied by the liquid propellant is then:

$$V_P = V_T - V_H$$

where $\quad V_P$ = total volume of liquid propellant

V_T = total volume of tank

The density of the liquid propellant ρ is established by the propellant temperature. Hence, the mass of liquid propellant M_P is:

$$M_P = V_P \, \rho_P$$

B. PROPELLANT LEAKAGE RATE DETERMINATION DURING SPACE FLIGHT

In any vehicle stage propellant tank (equipped as previously described) containing a small ullage volume of helium gas and subcooled liquid propellant, a decrease in tank pressure would indicate a propellant leak. As long as the tank pressure remains above the vapor pressure of the propellant, the mass of propellant within the tank can be determined as described within this paper. The leakage rate is given as:

$$\gamma = \frac{M_o - M_t}{t - t_o} \tag{2}$$

where $\quad \gamma$ = leakage rate, #M/time

t_o = time leak is discovered

t = time after leak is discovered

M_o = mass of propellant within the tank at time t_o

M_t = mass of propellant within the tank at time t

FIGURE 3 shows a schematic arrangement of this leakage determination system applied to the propellant tanks of a space vehicle.

SECTION III. INVESTIGATIONS REQUIRED TO ESTABLISH PROPOSAL FEASIBILITY

The accuracy of the measuring instruments must be evaluated to determine the system feasibility. The following is considered:

1. <u>Water Volume</u>. The water volume of the propellant tank must be determined and calibrated for low temperature shrinkage. This method is in current usage and therefore poses no particular problems.

2. <u>Pressure</u>. The measurement of pressure within the tank also is within the current state of the art. However, since there is a zero-gravity environment, buoyant forces are not present. Therefore, the measured tank pressure is independent of sensor location. Probe and readout sensitivity are expected to be about the same as is in current usage.

3. <u>Temperature</u>. Temperature probes indicating propellant temperature should be similar to those in current usage on vehicle propellant tanks. Due to heat transfer, temperature stratification may occur. Although this effect could be deleterious, it is not expected to be so during propellant transfer, due to turbulence. However, in the case of slow leakage rate detection, stratification effects are expected to be influential, as little turbulence is promoted. Therefore, stratification effects must be examined in light of the leakage system accuracy.

Temperature probes may prove necessary within the helium system. However, since helium has a high thermal conductivity, its temperature would be the same as the propellant temperature.

4. <u>Helium Mass</u>. The mass of helium used in this system is expected to be very small, i.e., the helium mass will constitute approximately 4 percent of the tank total volume when the propellant becomes liquified. The percentage error (ϵ_H) in measuring the helium volume will reflect a percentage error (ϵ_P) in determining the total propellant volume and is given by:

$$\epsilon_p = \epsilon_H \frac{V_H}{V_P}$$

For a system having a 4 percent helium ullage volume, the volumetric error in measuring the helium volume would be reflected as an error of $\epsilon_p = \frac{4}{96} \epsilon_H = \epsilon_H/24$. This unique aspect of the system contributes little to the total system inaccuracy. Therefore, the total system accuracy depends primarily on the accuracy in determining the total volume of the tank and the density of the liquid propellant. It is anticipated that laboratory methods will be employed for measuring the mass of helium used in the system.

5. <u>Bladder Porosity</u>. The porosity of the bladder may pose a problem, i.e., diffusion of the helium gas through the bladder walls might impair the measurement system. Further, the problem of developing a flexible bladder compatible with certain liquid propellants must be solved. It is anticipated that a bladder similar to an expulsion bladder currently being investigated would be required. Due to this problem an alternate concept is presented.

SECTION IV. ALTERNATE MASS MEASUREMENT SYSTEM CONCEPT

In the previous section, the use of a flexible bladder was described in conjunction with a mass measurement system for determining the mass of propellant transferred and propellant mass leakage. It was mentioned that diffusion of the gas contained within the bladder might impair the system, therefore, investigations were conducted to determine if a system could be devised which would eliminate the bladder. The following is a description of the propellant transfer.

1. Consider a nonvented transfer system and propellant tank as presented for the first proposal except that the bladder is deleted.

2. Prior to, or shortly after, the initiation of propellant transfer the helium is released within the vehicle propellant tank (FIGURE 4). The mass of liquid propellant transferred can immediately be determined with the gas law and Dalton's law of partial pressures.

3. Since the temperature of the propellant can be measured, the vapor pressure of the liquid propellant can be determined with tables or charts. The helium pressure is determined as:

$$P_H = P_T - P_{PV}$$

where P_H = pressure of helium

P_T = total pressure of tank

P_{PV} = vapor pressure of propellant

The helium volume is:

$$V_H = \frac{M_H Z_H R_H T_H}{P_H} = V_{PV}$$

where V_{PV} = volume of propellant vapor

The volume of liquid propellant then is:

$$V_P = V_T - V_H$$

The mass of liquid propellant within the tank is:

$$M_P = V_P \, \rho_P$$

SECTION V.   DISCUSSION OF ALTERNATE SYSTEM CONCEPT

1.   Although this system is similar to the initial concept, it is less accurate. This is a consequence of determining the helium volume as a function of the propellant vapor pressure and total tank pressure.

2.   The absorptivity of the propellant for helium must be investigated.

3.   A serious impairment to this system is that a leak would make mass determination impossible. This is true since helium gas can escape with propellant from the system.

SECTION VI.   CONCLUSION

The unknown thermodynamic relations for a given liquid propellant and helium gas may be used in conjunction with state of the art instrumentation to provide a mass measurement system comparable with terrestrial systems.

The proposed system employing a flexible bladder is recommended for this purpose since it is inherently more accurate than the system without the bladder. Furthermore, the recommended system is not impaired by the leakage of propellant from the propellant tank, rather it may be used to determine propellant leakage rate.
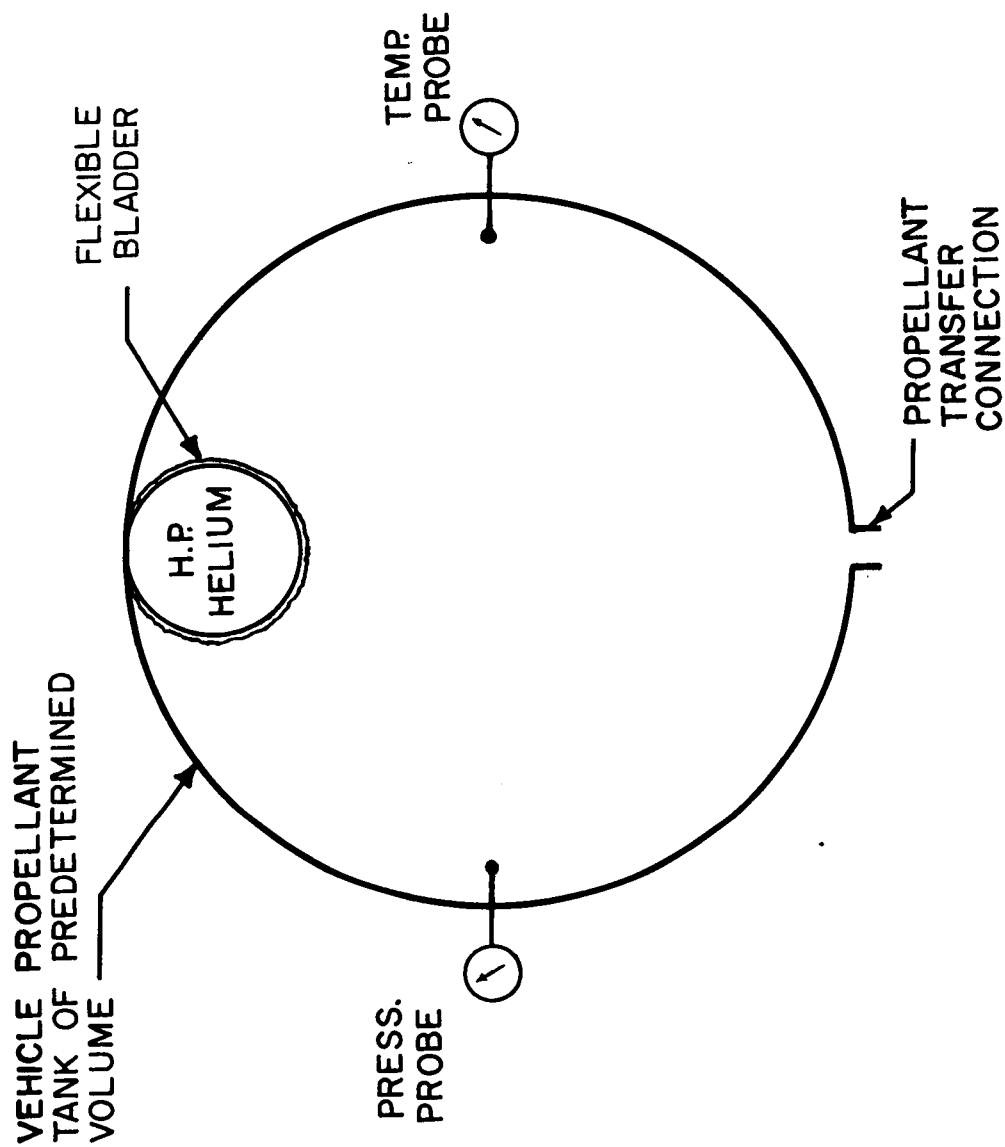
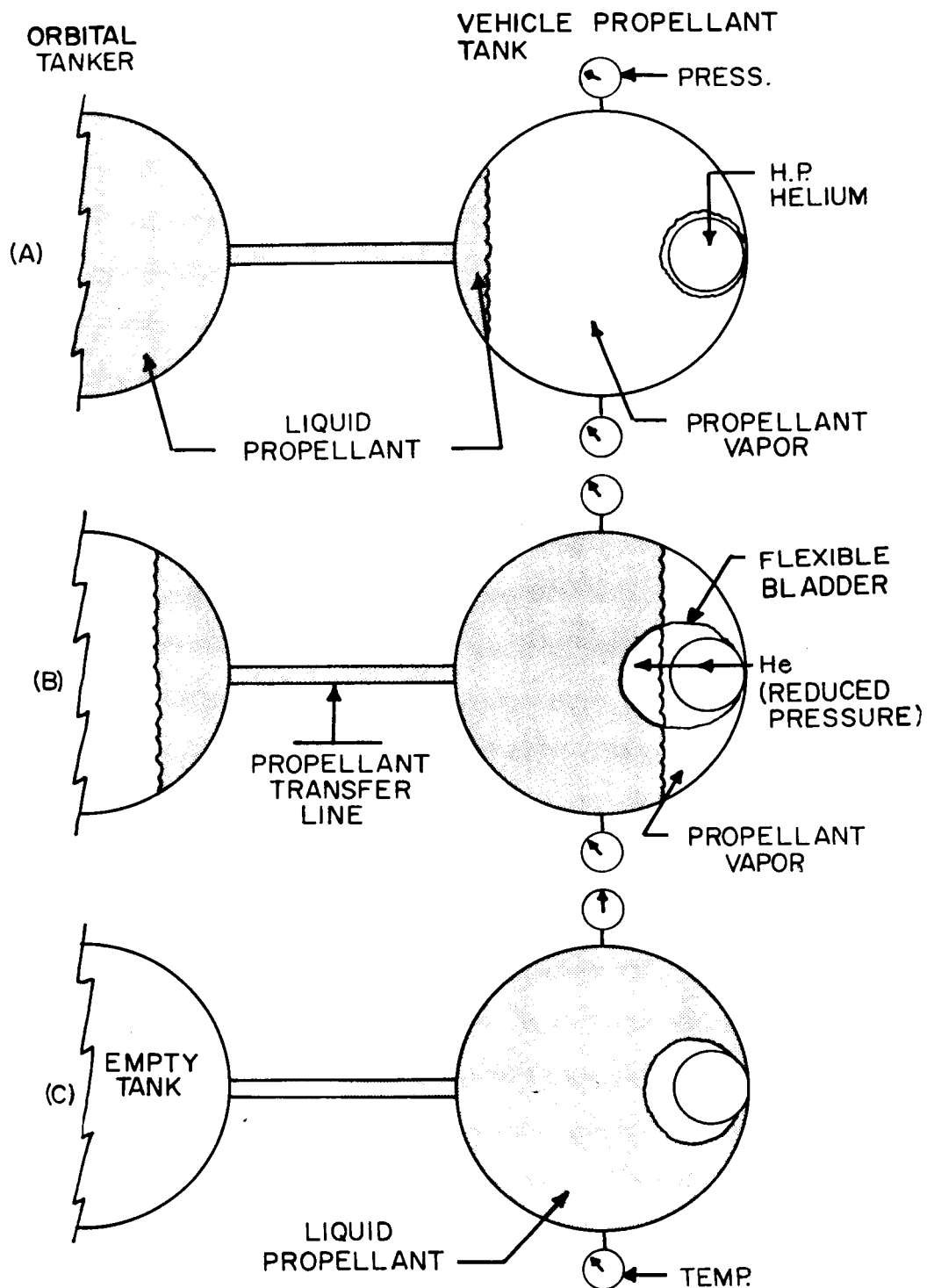FIGURE 1.   PROPOSED MASS MEASUREMENT SYSTEM INSTALLED IN VEHICLE PROPELLANT TANK

ORBITAL
TANKER

VEHICLE PROPELLANT
TANK

PRESS.

H.P.
HELIUM

(A)

LIQUID
PROPELLANT

PROPELLANT
VAPOR

FLEXIBLE
BLADDER

He
(REDUCED
PRESSURE)

(B)

PROPELLANT
TRANSFER
LINE

PROPELLANT
VAPOR

EMPTY
TANK

(C)

LIQUID
PROPELLANT

TEMP.

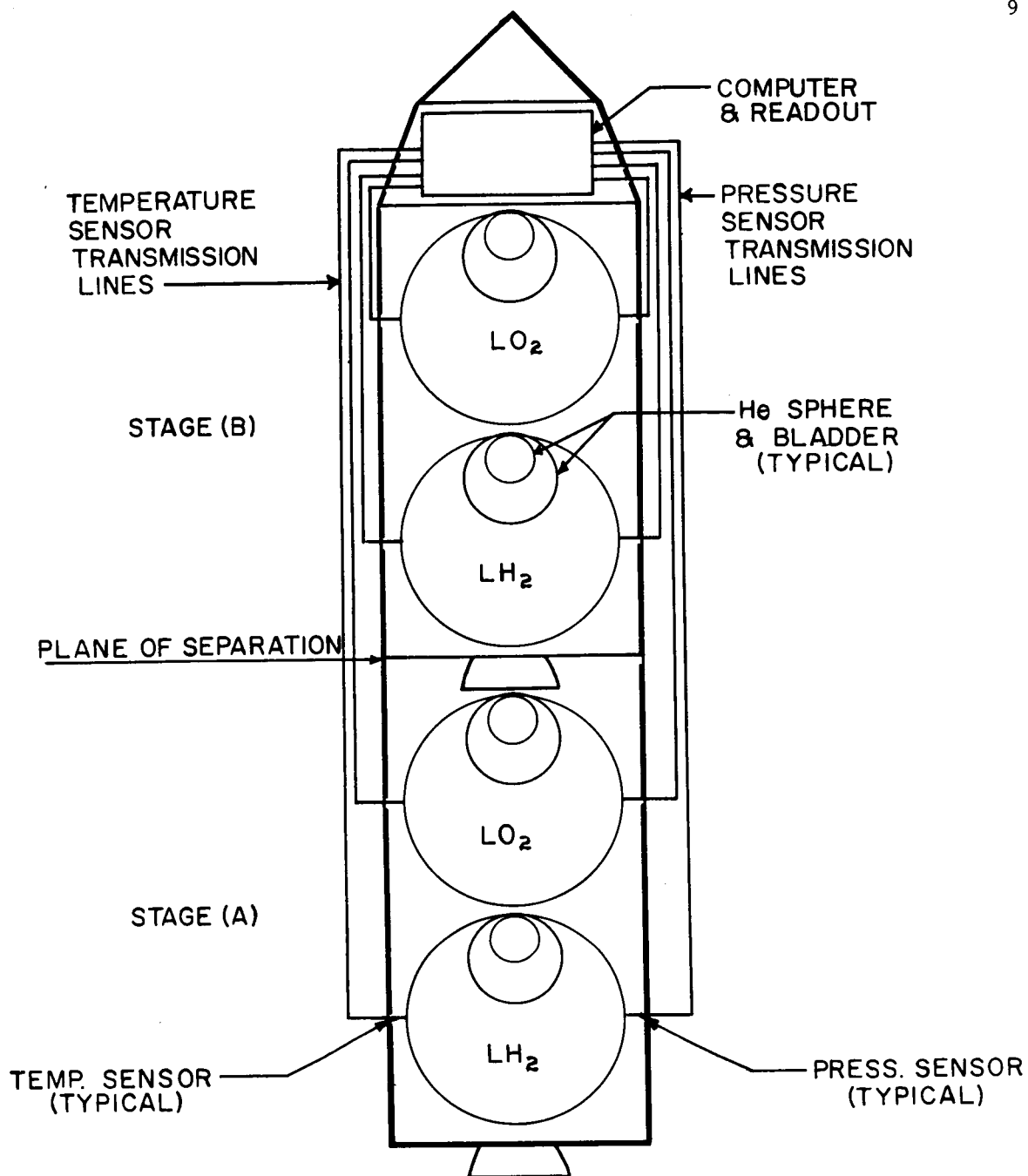FIGURE 2.   PROPELLANT TRANSFER-MASS MEASUREMENT SYSTEM OPERATION

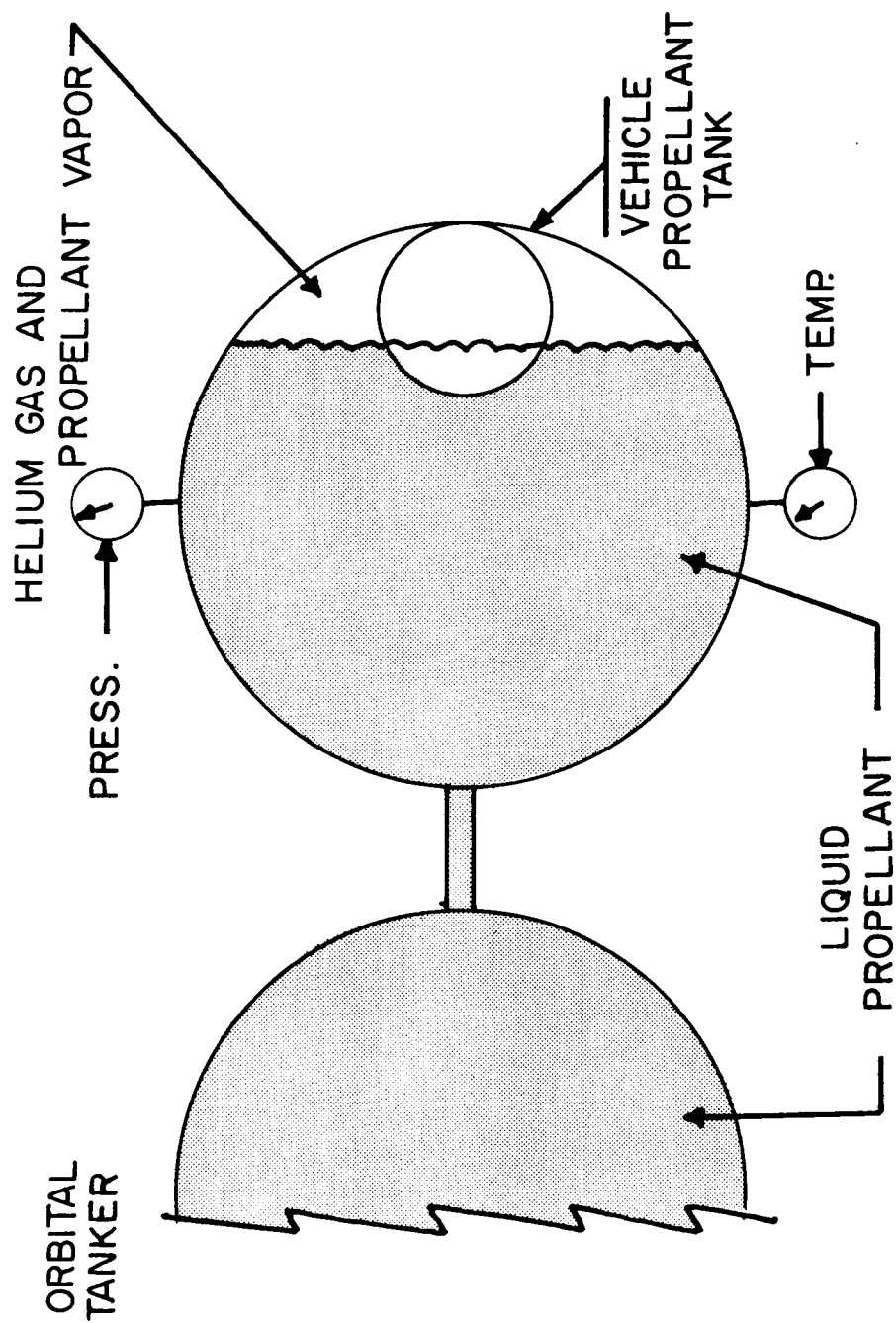FIGURE 3.   MASS MEASUREMENT SYSTEM INCORPORATED WITHIN A SPACE VEHICLE

FIGURE 4. PROPELLANT TRANSFER-ALTERNATE MASS MEASUREMENT SYSTEM PROPOSAL